The Sky in Edvard Munch's "The Scream"

Fred Prata*

Visiting scientist, Department of Atmospheric, Oceanic and Planetary Physics, University of Oxford, UK

Alan Robock

Rutgers University, New Brunswick, NJ, USA

Richard Hamblyn

Birkbeck College, University of London, UK

**Corresponding author address:* AIRES Pty Ltd, PO Box 156, Mt Eliza, Victoria, Australia

E-mail: fred_prata@hotmail.com

ABSTRACT

“The Scream” is a well-known painting by Edvard Munch (1863–1944). The Norwegian word used by Munch is “Skrik,” which can be translated as “shriek” or “scream”. “The Scream” may be of interest to meteorologists because of the quite striking representation of the sky. It has been suggested that the dramatic red-colored sky was inspired by a volcanic sunset seen by Munch, after the Krakatau eruption in 1883, that it was inspired by a sighting of stratospheric nacreous clouds and also that it is part of the artist’s expression of a scream from nature. The evidence for the volcanic sunset theory and Munch’s psyche are briefly reviewed. We provide support that Munch’s inspiration may have been from a sighting of nacreous clouds, observable from southern Norway during the winter months. We show that the colors and patterns of the sky in Munch’s painting match the sunset colors better if nacreous clouds are present. Their sudden appearance around and after sunset creates an impressive and dramatic effect. By comparing the color content of photographs and paintings of regular sunsets, volcanic sunsets, and nacreous clouds after sunset, with the color content of the sky in “The Scream”, the match is better with nacreous clouds present. If this conjecture is correct then Munch’s sky in “The Scream” represents one of the earliest visual documentations of a nacreous cloud display.

Capsule Summary

The sky in Edvard Munch's "The Scream" is compared with photographs of a display of nacreous clouds, and through the use of a color analysis a striking similarity is found.

1. Introduction

The representation of clouds and other meteorological phenomena in art has been recognised for some time as a source of potential data to describe aspects of the atmosphere long before the widespread use of quantitative measuring devices, e.g., Neuberger (1970), Brimblecombe and Ogden (1977), Thornes (1999), Zerefos et al. (2007), Zerefos et al. (2014). A notable example of this was the use of William Ascroft's pastel sketches (Ascroft 1888) showing dramatic sunsets that appear on the frontispiece of the Royal Society's publication "The Eruption of Krakatoa and Subsequent Phenomena" (Symons 1888). These sketches depict observations from Chelsea, London, on 26 November 1883 and show the effects that aerosols high in the atmosphere have on the color of the sky. We cannot be sure that the chromo-lithograph reproductions of the sketches accurately represent the spectral content of the sky, as we also cannot be sure that Ascroft himself accurately depicted the colors using the palette of crayons to him, but modern photographs of volcanic sunsets resemble these sketches well.

Hamblyn (2001) describes the origin of the systematic categorisation of clouds by Luke Howard. Clouds had hitherto been assumed to be ephemeral shapes in the sky. This "invention" had an immediate impact on the scientific community and was recognised at the time as an important paradigm. Howard's descriptions included sketches of various cloud types, but interestingly not all. Fikke et al. (2017) have hypothesised that the sky in “The Scream” has a striking similarity to mother-of-pearl or nacreous clouds. They discuss anecdotal evidence concerning the possibility that Munch observed these clouds whilst out walking with friends one evening, or perhaps on another occasion or occasions. They suggest that although Munch himself seems not to have regarded his observation as one of clouds (he refers to the sky), since this type of cloud was rare he may not have recognised that the atmospheric display was connected to the presence of high clouds. Here we discuss previous ideas concerning the inspiration behind Munch’s depiction of the sky. These include the volcanic sunset hypothesis, the idea that Munch used colors for symbolic meaning, for example red to represent passion and blood, and the nacreous cloud hypothesis of Fikke et al. (2017). The paper briefly discusses the first two ideas and then concentrates on the nacreous cloud hypothesis. Because the exact dates of the paintings and Munch’s motives are uncertain, this and previous discussion have been limited to conjecture. We also include some background on Munch, his art and his mental state. The main focus of this paper, however, is an objective color analysis of his paintings of “The Scream”, of photographs of volcanic sunsets and nacreous clouds. By analysing the color content and patterns of the depiction of the clouds and sky in “The Scream”, this study supports Fikke et al. (2017)’s suggestion that nacreous clouds provided the inspiration for his depiction of the sky in “The Scream”.

2. The art of Edvard Munch

Edvard Munch (1863-1944) was a Norwegian artist noted for his sombre motifs and expressionist style. Munch was the second child born to Christian Munch who was a very religious, stern and conservative man and had a strong influence on Edvard. His mother died in December 1868 of tuberculosis, a fate also suffered by his grandfather, Edvard Storm Munch, and who was insane at the time of his death. The hardships, grief, gloominess and Edvard's conviction that he would eventually succumb to insanity are believed to have influenced his artistic style and subject matter. Indeed the themes of blood and melancholy are present in many of his paintings.

Of relevance to this study, Munch is known to have been indifferent to dating his artwork (Prideaux 2012). This may have been due to his desire to keep his paintings with him and update them from time to time by adding brushstrokes, but also may have been due to his view that the chronology of his work only mattered when he considered the work finished (Prideaux 2012). He is also known to have dated his works going back many years before they were first exhibited, as well as producing many versions of the same painting. The relevance, as we shall see, is that it is difficult to say precisely when he first painted "The Scream" and indeed when he first conceived the idea.

The materials and paints used by Munch are also somewhat uncertain. He seems to have favoured using unprimed canvas or cardboard (see Figure 1, later). He did not use varnishes and was somewhat haphazard in the use of oils, pastels, crayons or pencils and would often mix these on the same canvas leading to a distinctive textural style. It must be stressed here that in attempting to apply a scientific analysis to an artwork of Munch we are greatly hindered by a lack of certainty over the chronology of his work, the materials used and not least, by his motivations.

a. The Scream

The most famous, certainly the most iconic, of Munch's works is "The Scream". The image is familiar to modern culture and has been reproduced many times and copied by other artists such as Andy Warhol and the cartoonist Gary Larson. There are four known color versions of "The Scream" (Figure 1), all believed to have been produced between 1893 and 1910, and one lithograph produced in 1895. Two of the color versions are the signed and dated 1893 version held by the National Museum of Art, Architecture and Design in Oslo, and a version with no date but thought to have been produced in 1910 and now held in the Munch Museum in Oslo. "The Scream" comes with a narrative that Munch himself penned in a diary dated 22 January 1892. There are actually several versions of this narrative written in Norwegian and in French, and the one given below is from the English translation of his selected prose (Guleng 2011, see: MM T 2760-56r):

I was walking along the road with two friends
– the sun was setting
– I felt a wave of sadness –
the Sky suddenly turned blood-red
I stopped, leaned against the fence
tired to death – looked out over
the flaming clouds like blood and swords
– the blue-black fjord and city –
– My friends walked on – I stood
there quaking with angst – and I
felt as though a vast, endless
scream passed through nature.

In the French version Munch writes: "... *pendant des nuages rouges comme du sang et comme des langues de feu.*" This translates as blood-red clouds and tongues of fire. Much has been made of this narrative and art historians recognise the motifs of red and blood associated with anxiety and often used by artists to describe pain, morbid feelings and angst. This "interruption" between the normal being and a highly charged emotional state with a feeling of detachment is a constant theme in the interpretation of the art of Munch. It is unclear whether this description can be treated as an actual observation (a real event) – Munch often added prose statements[1] to accompany his art and they exist in many different versions. Hilde Dybvik suggests that Munch followed the Kristiania Bohemians' tenet to "write one's own life" (Guleng 2011). Although there is no definitive evidence that this event actually happened, there are circumstantial clues that point to a physical location for the walk that fit well with the scene depicted in "The Scream" as well as with the prose commentary. There is a road near the city of Oslo in a commune called Ekeberg, close to Utsikten, that overlooks Oslo fjord and has a view towards the south west in the direction of the setting Sun during the winter months. The location is now marked by commemorative plaque to honour Munch. At the time that Munch may have made this walk, the road was a path and, interestingly, a slaughterhouse and a mental asylum were located nearby. It has been suggested that the idea of "The Scream" may have been influenced by the sound of animals being slaughtered nearby. A possible reason for Munch walking in this area, suggested by Sue Prideaux in her book "Behind The Scream" (Prideaux 2012), is that he was visiting his younger sister who had recently been admitted into the asylum. There are also speculations that Munch had seen an exhibit of a Peruvian mummy in Paris and this has influenced the the way the main figure in "The

[1]Referred to as 'prose poetry', see Guleng (2011), p.137.

Scream" is depicted, with a hairless, contorted face. The world of art history makes little comment on such influences and there is virtually no analysis of the sky in "The Scream", the main topic of discussion in this work. If the narrative is to be treated literally then there are some important remarks that provide clues to the cause of the dramatic sky. He mentions the Sun was setting and that the sky "suddenly" turned blood-red. He mentions "flaming clouds" and "swords". The word "wave" appears in the written statement and the sky is depicted as "wavy". This suggests that if the observation is to be treated as real, then it is likely that the colors were influenced by an appearance of clouds. Nacreous clouds fit this description well, as we shall see later.

Although many people look at the painting and think that the character is screaming, due to the open mouth, it is clear from Munch's narrative that it is the sky that is screaming, and the figure is covering his or her ears, in a futile attempt to smother the sound. Munch used the same setting to produce other paintings with the same red and yellow sky, mountains, and Oslo fjord in the background, such as "Despair" in 1892, another "Despair" in 1894, and "Anxiety", also in 1894. In these paintings, the sky has a much less wavy character, and the sky just curves to exactly match the mountains beneath. This argues against the interpretation that he is depicting nacreous clouds, at least in these later images.

b. Chronology

The generally accepted date of the first pastel version (tempera and crayon on cardboard) of "The Scream" is 1893. Later versions are dated to 1895 and also as late as 1910. The date for the version held at the Munch Museum in Oslo is disputed, although most experts agree on a date of 1910, while some argue for an earlier date in the 1890s. It is quite possible that Munch started work on this subject earlier, but “The Scream” was not seen in public until the exhibition at Unter den Linden in Berlin in the winter of 1893. The work would later become part of the “Frieze of Life” which also included “Angst” (1894) and “Despair” (1894), which both have a strong resemblance to “The Scream”. The problem with making a chronology of Munch’s work comes from his habit of not always dating and signing his work until he felt it to be complete. It is also known that he had wrongly dated some of his work (Ydstie 2008). The four color versions of “The Scream” are shown in Figure 1.

c. Interpretations

Robock (2000) first suggested that the red sky in “The Scream” was reminiscent of a volcanic sunset. Accepting the date of the work as 1893, Robock looked for a large eruption occurring in the year before that might have caused reddened skies in Europe. The Awu (Sangihe Islands, Indonesia) eruption of June 7–12 1892 seemed to fit this scenario and so he suggested this volcano as the culprit. This speculation was corrected later by Robock (2007) based on the work of Olson et al. (2004) who suggested it was the eruption of Krakatau in August 1883 that was the true cause for the remarkable blood-red clouds that Munch had described. Olson et al. (2004) seem to have come to this conclusion by accepting the date of the painting as 1893 but noting that there was little else that could have caused such a dramatic sky in that year. The argument then becomes somewhat interpretive in the sense that it must be accepted that Munch had seen a Krakatau sunset, most likely in the winter of 1883, remembered it and then painted it some 10 years later. There are numerous problems with this interpretation, not least that such a dramatic event in his life was not expressed in his art until so much later. So is it possible that Munch painted “The Scream” in

1883 or 1884? At that time, Munch was living the life of a Bohemian in Kristiania (now Oslo). He was 19 years old and had not yet decided to devote his life to art. Further, his expressionist style, of which “The Scream” is an example, had not yet developed – and would not be fully developed until after he had seen the works of Van Gogh, Gauguin and Monet on visits abroad. Another factor that points to a later date for the painting is that there are reasons why Munch may have been experiencing acute depression and anxiety. Munch’s father died in 1889 and this had a profound effect on Munch’s mental state. His younger sister Laura was also experiencing mental health problems and had been admitted into the asylum near Ekeberg. Munch lived in constant fear of having a mental breakdown himself. This combination of events could provide the backdrop and motivation for expressing his morbid feelings in his art. Olson et al. (2004) argue that a later date (much later than his actual observation) fits with other paintings he made that feature events from a much earlier experience in his life. The important point here is that he could only have seen a Krakatau sunset after late November 1883 and before March 1886, when the volcanic sunsets had disappeared over northern Europe. If we consider his whereabouts during this period and that it must have been a wintertime observation then it really narrows down the observation to the winter months of 1883. If we accept that the observation was real, then the possible candidates are an abnormal or particularly striking sunset, a volcanic sunset or some other meteorological phenomenon, not yet disclosed.

Fikke et al. (2017) report observations and photographs of a display of nacreous clouds in December 2014 from Oslo, Norway. They noted the similarity of the color and pattern of the nacreous cloud display to the sky in Munch’s “The Scream”. As also found here, Fikke et al. (2017) and

Olson et al. (2004) are unable to provide a likely date when Munch observed the "blood red" sky, but like Fikke et al. (2017) we favour an explanation based on an observation of nacreous clouds rather than a volcanic sunset. We believe the meteorological nacreous cloud explanation fits with the chronology, the geography and more importantly with the way the sky is depicted in "The Scream". Our evidence is presented in the following sections, and we approach this in a scientific manner rather than as an artistic interpretation. We also admit that it is impossible to know what was in the mind of Munch when he painted "The Scream" and hence we are making the same implicit assumption as Fikke et al. (2017), Robock (2000, 2007) and Olson et al. (2004) that the event (Munch's observation on the walk as described in his prose) actually occurred and that this was the subject matter for the painting. None of the interpretations depend on Munch painting "The Scream" while he watched the sun set so it is a matter of weight of evidence to decide which interpretation is more plausible. Art historians might argue that the actual observation is not important – the visual effect is the same whether he imagined it or whether it was based on a real experience. An imagined experience remains a completely plausible explanation.

3. Volcanic sunsets

The idea that the sky in "The Scream" was inspired by a volcanic sunset is pervasive; a web search for "The Scream" will most often include a reference to a volcanic connection. Indeed volcanic aerosols high in the atmosphere (typically 20 km or higher) produce some of the most spectacular red sunsets. The processes leading to highly reddened skies after the Sun has set are well-known and involve selective scattering of light. SO_2 emitted during volcanic eruptions is converted to sulfate aerosols (H_2SO_4 in aqueous solution – typically 75% acid to 25% water) that form stable layers in the lower stratosphere. These high-altitude layers contain millions of small-sized aerosols (diameters $< 1\ \mu$m) that can scatter light, but because their size is comparable or larger than the wavelength of visible light, that scattering occurs in the Mie region. The sunsets due to these aerosols have a different appearance to ordinary sunsets where Rayleigh scattering (strong wavelength and particle size dependence) is responsible for the reddening. The scattering from volcanic aerosols becomes noticeable when the light path from the Sun grazes the atmosphere, while still intersecting the aerosol layer. This leads to two noticeable effects: reddening due to the selective scattering of light as it takes a long path through the atmosphere, and an afterglow usually strongest 20–30 minutes after sunset due to scattering of the reddened light off the aerosol layer. Almost no blue light is intensified by this scattering process but there is a small enhancement of green light. Since the stratosphere is stable (the temperature increases with increasing height) there is a tendency for the aerosols to form in layers. The well-known Junge layers are the stable background layers formed by repeated injection and depletion of these aerosols in the stratosphere over time (Junge 1955). Volcanic sunsets get progressively stronger as the Sun sinks lower below the horizon and then they diminish as the sunlight is eclipsed by the Earth and the light rays no longer reach the layer. The dramatic effect can last for 20 minutes or longer and the speed of onset depends on the latitude of the observer: the Sun sets faster at the equator than at 60 °N. The spectral content of the light from a non-volcanic sunset is depleted in blue light, has more longer wavelength light closer to the horizon and culminates in the strongest enhancement at the red end of the spectrum after which the sensitivity of our eye to longer wavelengths ends. A typical eye has a maximum sensitivity at $\sim$550 nm, dropping to 20% at 489 nm and 637 nm (Goss and West 2002).

Under twilight conditions there is a shift in sensitivity towards shorter wavelengths. Non-volcanic sunsets can become more dramatic and noticeable if there are high-level clouds that can also scatter light back towards the observer. Figure 2 shows a photograph of a volcanic sunset captured from an aircraft flying at 38,000 ft (11,582 m) over the South Pacific in July 2011, following the eruption of Puyehue-Córdon Caulle in southern Chile. This photograph has been selected (among the many fine examples available) because it illustrates all the main features of a volcanic sunset that show the strong reddening of the sky near the horizon (in shadow), changing through orange to yellow and finally to the deep blue of the outer atmosphere. There are noticeable stratifications, due to aerosol layers. The question of whether Munch could have seen a sunset due to the eruption of Krakatau was raised by Olson et al. (2004), and also later in Olson (2014), who simply assumed he would have had the opportunity. Fikke et al. (2017) also address this matter, suggesting that the stratospheric haze due to Krakatau was rather diffuse as observed from latitudes around 60°N. The sunsets were most vivid in the winter of 1883 over Europe. The Symons (1888) report provides the best consolidated set of observations of optical phenomena due to Krakatau aerosols and includes a map of the approximate northern limit of the main sky phenomena by the end of November 1883. This is based on the relatively sparse set of observations available, but it clearly shows that Krakatau optical phenomena could have been seen from southern Norway at the start of the winter of 1883. There are observations of "glows" on 29 and 30 November 1883 from Kristiania and these continued until February 1884, although there are no specific dates given. The glows are reported to have diminished by March 1884 in Europe. It is highly unlikely that Krakatau optical phenomena would have been visible as late as the 1890s over southern Norway. This gives a range of dates from late November 1883 until February 1884 for Munch to have seen a glow. But what of an abnormally bright sunset of non-volcanic origin? There are many examples of these, e.g., Minnaert (1974). They are particular striking when the atmosphere is clear (large dust and other particles in the troposphere tend to reduce the color of the sky) or when there are clouds that can reflect and enhance the scattering of the Sun's reddened light. The sequence of colors from such a sunset usually starts at the horizon with red, orange-red, yellow, and then deep blue, but there can be subtle differences depending on the angle of the Sun below the horizon (Minnaert 1974, page 295, Fig.169). One way to decide whether Munch tried to reproduce what he had seen is to look at the sequence of colors. We examine this in a later section.

4. Nacreous clouds

In the insightful investigation made by Olson et al. (2004) of the circumstances contributing to the depiction of the sky in "The Scream", they notes that after searching for possible causes of the blood-red sky over Oslo fjord, none were apparent in 1893. However, as shown by Fikke et al. (2017) the appearance of nacreous clouds, a very dramatic phenomenon and hardly known at the time, could have caused such a sky. Minnaert (1974) describes the phenomenon this way: *"Sometimes, these clouds are striped, undulating, cirrus like; at other times, the entire cloud bank is almost one color, with spectral colors along the edges in oblong horizontal rows..."* and *"The whole scene is indescribably lovely and majestic."* Minnaert is describing nacreous clouds, known by atmospheric physicists as one type of polar stratospheric clouds (PSCs) and by the more descriptive moniker of mother-of-pearl clouds (MPCs). He goes on to write that they are visible from southern Norway in winter. Nacreous clouds generate very dramatic skies and are most noticeable as the Sun sets, when the color of the clouds reddens and could certainly be described as "blood red" as the photographs shown later demonstrate. Munch had ample opportunity to see such a display. When not travelling abroad, he lived in southern Norway and the direction and location of the scene depicted in "The Scream" also fits with the direction and location for nacreous cloud observations. Furthermore, as shown next, nacreous clouds observations from southern Norway were documented on at least five occasions in 1892. Nacreous clouds should not be confused with the much higher altitude noctilucent clouds (Gadsden and Schröder 1989), that seem to have been documented and photographed in the mid-1880's (Dalin et al. 2012).

a. Occurrence

Mohn (1893) describes observations of nacreous clouds made in 1892 from England and Norway, while Størmer (1929) discusses these clouds in a systematic manner from a series of photographs made from sites in Oslo, southern Norway in 1926. Størmer (1929) notes that between 1872 and 1892 nacreous clouds were observed from Norway, but that after 1893 he did not observe them again until 1926, despite careful observations. Stanford and Davis (1974) provide a list of dates when these clouds were observed from Europe; in 1892 there are five confirmed observations from Norway and there are observations in every year before that until 1881, except 1883 and 1888. While it is generally considered that these clouds are rare, apparently from the right location (southern Norway) and at the right time of year (winter) there is a good chance of observing them[2]. Fikke et al. (2017) also show some spectacular photographs of nacreous clouds taken in late December 2014. Munch therefore likely had the opportunity to witness a nacreous

[2]FP has observed them from southern Norway on four separate occasions during 2008–2014.

cloud display from exactly the location that he made his walk with his two friends, looking in the right direction towards the southwest during many days in most of the winters between 1872 until 1892. In the 1880s and 1890s these clouds had not been classified and their height and occurrence were unknown.

Hesstvedt (1958) studied 168 cases of observations of MPCs and found a mean height of 24 km, a predominance of wintertime observations (December–February), a preferred location to the eastern side of the Norwegian mountains and a correlation with the synoptic weather pattern. Stanford (1973) provides a physical basis for their formation and occurrence and they are discussed further by Fikke et al. (2017).

b. Known photographs

The earliest photographs of nacreous clouds are given by Størmer (1926) and there are numerous examples of photographs of these clouds now available on the web. The website: `http://www.atoptics.co.uk/` has some striking examples of nacreous clouds and the recent article by Fikke et al. (2017) also includes some fine examples. In January 2008 there was a particularly vivid display of these clouds and one of us (FP) was lucky enough to be in southern Norway (Leirsund $\sim 60°$N, $\sim 11°$E) and make a series of photographs looking towards the southwest as the Sun set. The change in the appearance of the clouds as the Sun disappeared below the horizon was remarkable: the sky reddened and the full spatial extent of the clouds became more evident. Part of the series of photographs is shown in chronological order in Figure 3. Before sunset, the clouds appeared cirrus-like (as Minnaert noted), white with only a hint of the spectacular colors to come. A short time later, as the light diminished, hues of blue, green, pink and red began to emerge. The wavy nature of the clouds became clearer and the progression of colors followed an intermittent pattern with blues and reds mixed in a wavelike structure. Finally, as the Sun set the clouds became reddened, appearing very bright and vivid but with the wavelike nature still noticeable. A comparison between a section of the sky in “The Scream” (two versions), a section from a photograph of nacreous clouds and a section from the Puyehue-Córdon Caulle photograph are provided in Figure 4. While all four panels show reddened skies, there is a striking resemblance between the slies of “The Scream” and those of the nacreous clouds, in pattern and color structure. The waviness in the sky in “The Scream” is absent in the volcanic sunset. The alternating patterns of colors in “The Scream” is evident in the nacreous cloud photograph and there is no uniform progression of color from red to deep blue in “The Scream” that is so clear in the Puyehue-Córdon Caulle sunset. The ‘eye-like’ structure in the middle of Figure 4(a) is often noticeable in nacreous cloud photographs. What more appropriate sight in the sky could there have been to ignite Munch’s morbid thoughts than a turbulent cloud structure full of reds and oranges? There is a certain iridescence in nacreous clouds that is not reproduced in “The Scream”. This could be because of the limited materials available to Munch (see Singer et al. (2010) for a detailed analysis), or because after sunset the iridescence is less pronounced (see Fig. 3, bottom two photographs). “The Scream” has never been restored (Ydstie 2008) and it must have been much brighter when first produced. Singer et al. (2010) analysed the pigments used in several of Munch’s paintings including both versions of “The Scream”. They founnd that Munch’s palette was not extensive and also that some of his paintings were left outside, suggesting that they were deliberately left to ‘weather’. The original paintings may have been more vibrant than what we see now. Nevertheless the main features that separate nacreous clouds from all other types, the progression of colors, the waviness, and their appearance after sunset suggesting great height, are all captured in the sky over Oslo fjord as depicted in “The Scream”.

5. Color analysis

In an attempt to be as objective as possible with our interpretation of Munch’s sky we analysed the relationship between the colors in photographs of sunsets and nacreous clouds as well as in various paintings that depict red skies. Of course interpretation of color itself is subjective and there is no generally accepted relationship between perceived color and spectral wavelength. A quantitative approach would seem to require that the color representation in both paintings and the photographs bore a known relationship to the spectral content of the scene being depicted (or photographed). In this approach the relationship between the instrument being used to measure the color content (the eye in the case of the artist and a charged coupled device in the case of a modern photographer) and the spectral content of the scene must be known. Finally, in the case of the artist, the palette of available colors may not be sufficient to reproduce the color content of the scene. This leaves aside the possibility that the artist may not wish to duplicate exactly the color content of the scene. Nevertheless there are tools that can allow us to interpret the relationship between different colors as they are portrayed in a photograph or painting.

a. The HSL color wheel

The Hue-Saturation-Lightness (HSL) wheel (e.g., Munsell et al. 1950; Feisner and Reed 2013; Kasson et al. 1995; Weeks et al. 1995) is a method to transform the colors in an image to reveal spectral color content. The HSL conversion has been used to study images in art previously (Ivanova and Stanchev 2009). The usual interpretations of these color qualities are: hue is what is normally thought of as ‘color’, e.g., red, green, blue, and so; saturation, sometimes referred to as chroma, may be thought of as dullness or vividness, and lightness represents the intensity, e.g., a light or dark color.

The analysis of the images and mapping on to the HSL color wheel proceeds by computing the RGB components of the image, in Joint Photographic Experts Group (JPEG) format. A Python programming language algorithm was written to extract the color table from the images. The RGB color table was then converted to the HSL color wheel and plotted. The hue (H) progresses around the circumference of the wheel (measured in degrees), while the saturation (S) lies in the radial direction. In this two-dimensional plot, the lightness L variation is not shown as it varies in a direction orthogonal to the H and S axes, that is, out of the page. It is possible to construct the plot as a cylinder but here we simply report the mean lightness value.

The HSL color wheel analysis was used on sections of three photographic images and a section from the 1910 version of “The Scream”. The image sections and their corresponding HSL color wheels are shown in Figure 5. The top panels show an example from a portion of an image containing a rainbow. A perfectly vivid rainbow would have colors evenly spread around the circumference of the wheel at large radial values (close to 1 for a highly vivid rainbow). Compare this wheel with that from a volcanic sunset (right-hand, top panel) and it can be seen that certain colors (greens, yellows) are poorly represented, but that the blue hues are more abundant and more vivid. The rainbow image is about 10% lighter than the volcanic sunset, as may be expected since the illumination is likely lower for the sunset. The color wheel for “The Scream” (bottom, left panel) is more similar to that for the nacreous cloud (bottom, right panel) than either the rainbow or sunset wheels. In particular the ‘flaring’ of the hues within the pink-red section of the wheel is striking and characteristic of nacreous clouds. The saturation of the colors in “The Scream” is greater than that in the photograph of the nacreous clouds. This could be due to the limited palette of colors available to Munch but also due to the degradation of the painting over time.

b. Pattern analysis

A distinctive feature of “The Scream” is the pattern of waviness of the clouds in the sky, or in the sky itself if it is interpreted as cloudless. This is generally not seen in red sunsets and volcanic sunsets, where the cloudless sky tends to be variegated and the sky with clouds tends to have variations but little or no waviness. It is possible to investigate the amount of waviness objectively by taking vertical sections through the sky part of “The Scream” and comparing this with vertical sections through photographs of sunsets. This is done by analysing the RGB components separately. Figure 6 shows vertical sections through a photograph of a volcanic sunset, through a photograph of nacreous clouds and finally through a section of the sky in “The Scream”. The waviness is apparent in both the nacreous cloud photograph and “The Scream” but much less so in the sunset. The relationship of the RGB components is also different in the volcanic sunset, where the order of the size of the components with line number (which may be interpreted as elevation) changes from R, G, B to B, G, R. No such change occurs in the nacreous cloud photograph or the section of “The Scream”, where the order is predominantly R, G, B, except in a few places where G and B are swapped and at the lowest part of "The Scream" where the color is dark grey (R, G, B equal). This order of the color components does not resemble the order expected in a volcanic sunset.

The volcanic sunset photograph was taken in a cloudless sky and one might expect more variation in the order of the color components when clouds are present. To investigate this we have analysed 8 photographs of red sunsets with clouds present and analysed 16 sections of the colored skies from 12 separate photographs of Ascroft's sketches of the Krakatau sunsets observed near London. The Ascroft photographs were taken at Blythe House, where they are archived by the Science Museum, London, using a 24 megapixel Nikon camera under artificial (fluorescent) lighting, without a flash. All camera processing features were turned off and a color temperature of 5000 K was used, which is typical for accurate representation of colors in art galleries. The sections are shown in Figure 7. As before, vertical transects were taken through the sections; in this case an average of 10 pixels was taken along the central line of each section. The means and standard deviations for the RGB color components were derived and are shown in Figure 7. There is a separation of the R, G and B components in an order similar to that found for the nacreous cloud and "The Scream" sections. The waviness is less pronounced and there is a slight tendency for the G and B color components to increase towards the higher elevation, but less pronounced than in the volcanic sunset section. There is little doubt that Ascroft was sketching the sky and cloud colors associated with volcanic aerosols, and the similarity of the order of the RGB components (but not the waviness) with "The Scream" is apparent. Many of Ascroft's sketches include what are obviously colored clouds and these clouds tend to redden an otherwise blue or dark blue sky, resulting in more R color component in the sketches at higher elevation.

Further photographs of volcanic clouds, many containing clouds were obtained from various sources and subjected to the color pattern analysis. Nine sections from nine different photographs are shown in Figure 8. Many more photographs of volcanic sunsets can be found here: `http://www.spc.noaa.gov/publications/corfidi/sunset/`. The volcanic sky sections were analysed in exactly the same manner as the Ascroft sky sections. The results are shown in Figure 8. The pattern of the variation of the RGB components with elevation is different to that of the Ascroft sections. Here there is a decrease in the R color component with elevation and an increase of the B component and very little change in the G component. The variation of each color component with elevation is very smooth, probably reflecting the fact that in these nine sections clouds were less dominant. It can be surmised that the variation with elevation of each individual component is due to clouds, while the change in count value (increasing color brightness) with elevation, and its relative change between the RGB components, is due to the phenomenon producing the sky colors. The analysis here seems to support the notion that the sky in "The Scream" contains clouds and that the change in color component brightness with elevation as well as the relative change, are more similar to that found in nacreous cloud photographs. We also examine the pattern of colors in a spectacular sunset, but one that is not affected by unusual aerosols. The example used is a section from a photograph of a sunset over Port Philip Bay, Melbourne, Australia taken in March 2017 from an elevation of 150 m (a.s.l.) when the view of the sky contained some clouds but otherwise was free of volcanic aerosols. The sunset was particularly red, with just a few clouds to add structure to the pattern of colors. Figure 9(a) shows the mean and standard deviation of a 20 pixel wide vertical transect of the RGB color components. The transect is shown (rotated 90 degrees clockwise) inset and aligned with the line number and Fig. 9(b) shows the larger section taken from the photograph with the location of the vertical transect indicated. The sequence of colors is, as before, R largest count, followed by G and B. In this case the brightness changes little with elevation (line number) except where there are cloud layers. At those locations the variation of the count value in all three components increases. This is but one example; it would appear that with the right distribution of cloud layers in the sky, variations in brightness or waviness could be reproduced to appear similar to the waviness seen in “The Scream”. Another photograph analysed contains both a red non-volcanic sunset and a nacreous cloud display. Performing the same analysis on a section of this photograph (Figure 9(c),(d)) shows the waviness structure in the RGB color components and the smoother variation of the sunset at lower elevation. These analyses provide an objective means to distinguish between the sequence of colors generated by volcanic sunsets (with and without clouds), spectacular (non-volcanic) sunsets (with and without clouds), nacreous cloud displays and, in one case, a combination of a non-volcanic sunset and a nacreous cloud display in the same photograph, and so having the same atmospheric conditions.

6. Conclusions

The sky depicted in Munch’s “The Scream” has a remarkable similarity to the patterns and colors seen in a display of nacreous clouds (Fikke et al. 2017). Such clouds are observed on rare occasions during cold winter months in the southern part of Norway, where the meteorological conditions are conducive to their formation. Edvard Munch was prone to spend time outdoors and many of his artworks include depictions of skies and country scenes. Previous researchers have suggested that Munch may have seen a volcanic sunset due to Krakatau and painted the sky in "The Scream" based on a memory of that event. But the recent article by Fikke et al. (2017) suggests the painting may have been inspired by a sighting of nacreous clouds. There appears to be little definite evidence of exactly what the event was, if any, that inspired Munch to paint the sky in that way. Although he wrote a commentary stating it was an actual observation that inspired him, it is known that Munch was prone to include prose with his art, sometimes after he had painted the work. Munch is also known to have been a poor chronicler of his work and there are even suggestions that he dated work much later than he actually painted it. This lack of factual evidence makes conclusions concerning his motivation rather difficult. Thus an interpretation that the painting was inspired by a volcanic sunset or motivated by his mental state cannot be ruled out. Instead here we provide support to an alternative hypothesis for Munch's sky based on the similarity of the painted image with photographs of nacreous cloud displays. Munch had ample opportunity to observe nacreous clouds and they were noted (but not depicted) in records during the period 1883–1910, during which it is believed Munch painted several versions of "The Scream".

The color analysis presented attempts to add some quantitative assessment of the color patterns and spectral content of "The Scream" compared with photographs of volcanic sunsets, non-volcanic sunsets, and nacreous clouds. While we readily admit that the interpretation of color in art and in photographs is problematic, there are at least indications that the color variations and order of the RGB color components in "The Scream" better match those of a nacreous cloud display than a cloudless volcanic sunset. Similar suggestions regarding the wave-like features were made by Fikke et al. (2017). Finally, if Munch did indeed observe and then paint the sky in "The Scream" based on a nacreous cloud display, then this in all likelihood would represent the first graphical depiction of a type of cloud largely unknown to meteorology at the time. In this context, this hypothesis will be relevant to those interested in clouds and in historical aspects of the development of cloud science in meteorology.

Acknowledgments. FP is grateful to the staff and curators of the Munch Museum and the National Gallery of Norway for helpful conversations. AR is supported by NSF grant AGS-1430051. Charlotte Elliston (Science Museum, London) is thanked for her help with access to the Blythe House collection of Ascroft's Krakatau sketches and for providing very useful advice on the catalogues. Captain Klaus Sievers (Lufthansa) is thanked for providing his photographs of volcanic sunsets.

References

Ascroft, W., 1888: *A catalogue of sky sketches from September 1883 to September 1886*. Science Museum, London, 18 pp.

Brimblecombe, P., and C. Ogden, 1977: Air pollution in art and literature. *Weather*, **32 (8)**, 285–291.

Dalin, P., N. Pertsev, V. Romejko, and H. Volkert, 2012: Notes on historical aspects on the earliest known observations of noctilucent clouds. *History of Geo- and Space Sciences*, **3 (1)**, 87–97.

Feisner, E. A., and R. Reed, 2013: *Color studies*. A&C Black.

Fikke, S. M., J. E. Kristjánsson, and O. Nordli, 2017: Screaming clouds. *Weather*, **72 (5)**, 115–121, doi:10.1002/wea.2786.

Gadsden, M., and W. Schröder, 1989: *Noctilucent clouds*. Springer, 148 pp.

Goss, D. A., and R. W. West, 2002: *Introduction to the optics of the eye.* Butterworth-Heinemann, 234 pp.

Guleng, M. B., 2011: *e.Munch.no – Text and image.* Munch Museum, Oslo, 303 pp.

Hamblyn, R., 2001: *The invention of clouds*. Picador, 292 pp.

Hesstvedt, E., 1958: Mother of pearl clouds in Norway. *Geophysics Norvegia*, **XX (10)**, 1–29.

Ivanova, K., and P. Stanchev, 2009: Color harmonies and contrasts search in art image collections. *Advances in Multimedia, 2009. MMEDIA'09. First International Conference on*, IEEE, 180–187.

Junge, C., 1955: The size distribution and aging of natural aerosols as determined from electrical and optical data on the atmosphere. *Journal of Meteorology*, **12 (1)**, 13–25.

Kasson, J. M., S. I. Nin, W. Plouffe, and J. L. Hafner, 1995: Performing color space conversions with three-dimensional linear interpolation. *Journal of Electronic Imaging*, **4 (3)**, 226–250.

Minnaert, M. G. J., 1974: *Light and color in the outdoors*. Springer-Verlag, 415 pp.

Mohn, H., 1893: Irisirende wolken. *Met. Zeit.*, 81–97.

Munsell, A. H., and Coauthors, 1950: *Munsell book of color*. Munsell Color Co.

Neuberger, H., 1970: Climate in art. *Weather*, **25 (2)**, 46–56.

Olson, D., 2014: *Celestial Sleuth*. Springer.

Olson, D., R. Doescher, and M. Olson, 2004: When the sky ran red: The story behind the scream. *Sky & Telescope*, **107 (2)**, 29–35.

Prideaux, S., 2012: *Edvard Munch. Behind the scream.* Yale University Press, 391 pp.

Robock, A., 2000: Volcanic eruptions and climate. *Reviews of Geophysics*, **38**, 191–219.

Robock, A., 2007: Correction to volcanic eruptions and climate. *Reviews of Geophysics*, **45**, doi: 10.1029/2007RG000232.

Singer, B., T. E. Aslaksby, B. Topalova-Casadiego, and E. S. Tveit, 2010: Investigation of materials used by edvard munch. *Studies in Conservation*, **55 (4)**, 274–292.

Stanford, J. L., 1973: On the physics of stratospheric (nacreous) cloud formation. *Tellus*, **25 (5)**, 479–482.

Stanford, J. L., and J. S. Davis, 1974: A century of stratospheric cloud reports: 1870-1972. *Bulletin of the American Meteorological Society*, **55 (3)**, 213–219.

Størmer, C., 1926: Photograms of auroræ in southern Norway. *Nature*, **117**, 855–856.

Størmer, C., 1929: Remarkable clouds at high altitudes. *Nature*, **123**, 260–261.

Symons, G. E., 1888: The eruption of Krakatoa and subsequent phenomena. *Royal Society of London*, 627.

Thornes, J. E., 1999: *John Constable's skies: a fusion of art and science*. A&C Black.

Weeks, A. R., C. E. Felix, and H. R. Myler, 1995: Edge detection of color images using the hsl color space. *IS&T/SPIE's Symposium on Electronic Imaging: Science & Technology*, International Society for Optics and Photonics, 291–301.

Ydstie, I. E., 2008: *The Scream. Munch Museum*. Vogmostad & Bjork AS., 105 pp.

Zerefos, C., V. Gerogiannis, D. Balis, S. Zerefos, and A. Kazantzidis, 2007: Atmospheric effects of volcanic eruptions as seen by famous artists and depicted in their paintings. *Atmospheric Chemistry and Physics*, **7 (15)**, 4027–4042.

Zerefos, C., and Coauthors, 2014: Further evidence of important environmental information content in red-to-green ratios as depicted in paintings by great masters. *Atmospheric Chemistry and Physics*, **14 (6)**, 2987–3015.

LIST OF FIGURES

FIG. 1. Four versions of "The Scream". Starting from the left: 1893 tempera on cardboard (Nasjonalmuseet for kunst arkitektur og design, Oslo); 1895 pastel on cardboard (sold at Sotheby's for US$119,922,600 to Leon Black on 2 May 2012); 1910(?) tempera on hard cardboard (Munch-museet, Oslo); 1893 crayon on cardboard (Munch-museet, Oslo). The 1910(?) version (panel 3 from left), on display at the Munch museum (Ydstie 2008). The "?" following the date is to indicate that the actual date is contested, some believing it is contemporary with the 1893 version. The work is unsigned and undated.

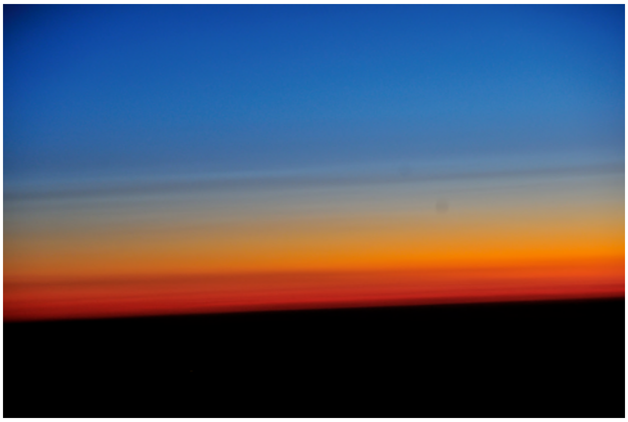

FIG. 2. Volcanic sunset of the South Pacific due to aerosols from the Puyehue-Córdon Caulle eruption, southern Chile on 5 June 2011. Photograph taken by F. Prata on 11 July 2011.

FIG. 3. Series of photographs of nacreous clouds taken on the evening of 20 January 2008 from Leirsund, southern Norway. Top-left: 15:08:56; top-right: 15:32:47; middle-left: 15:33:17; middle-right: 15:34:20; bottom-left: 15:46:35; bottom-right: 15:48:11. Time of sunset was 15:00. All times are UTC on 20 January 2008. Location: 59° 59’ 38.84 N, 11° 06’ 21.20 E, 181 m a.s.l. (Photographs taken by F. Prata)

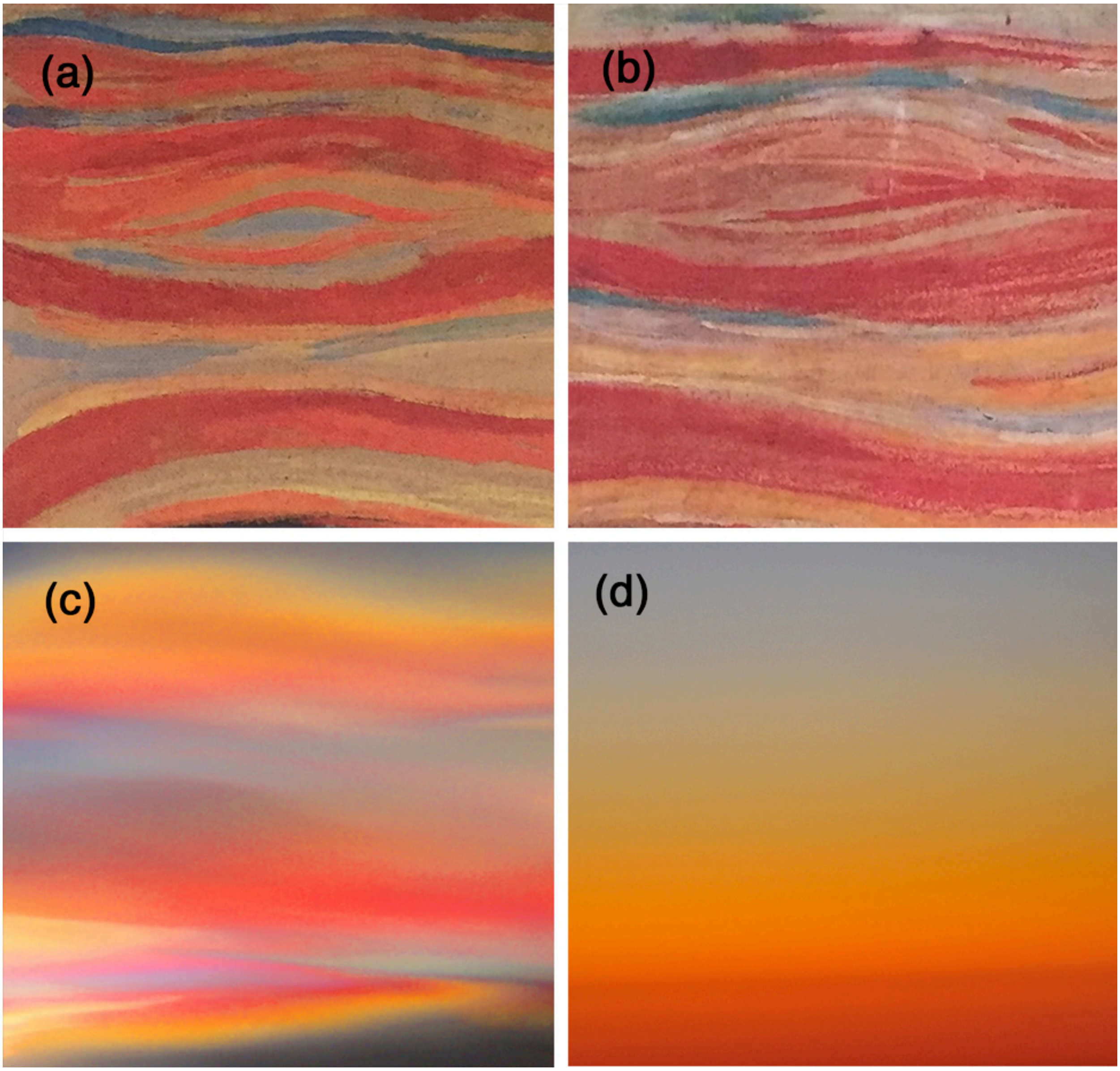

FIG. 4. Intercomparison of part of the sky in "The Scream" with nacreous clouds and a volcanic sunset. (a) Top-left: Section from the 1910 version. (b) Top-right: Section from the 1893 version. (c) Bottom-left:Section from a photograph of Nacreous clouds. (d) Bottom-right: Section from photograph of a Puyehue-Córdon Caulle sunset.

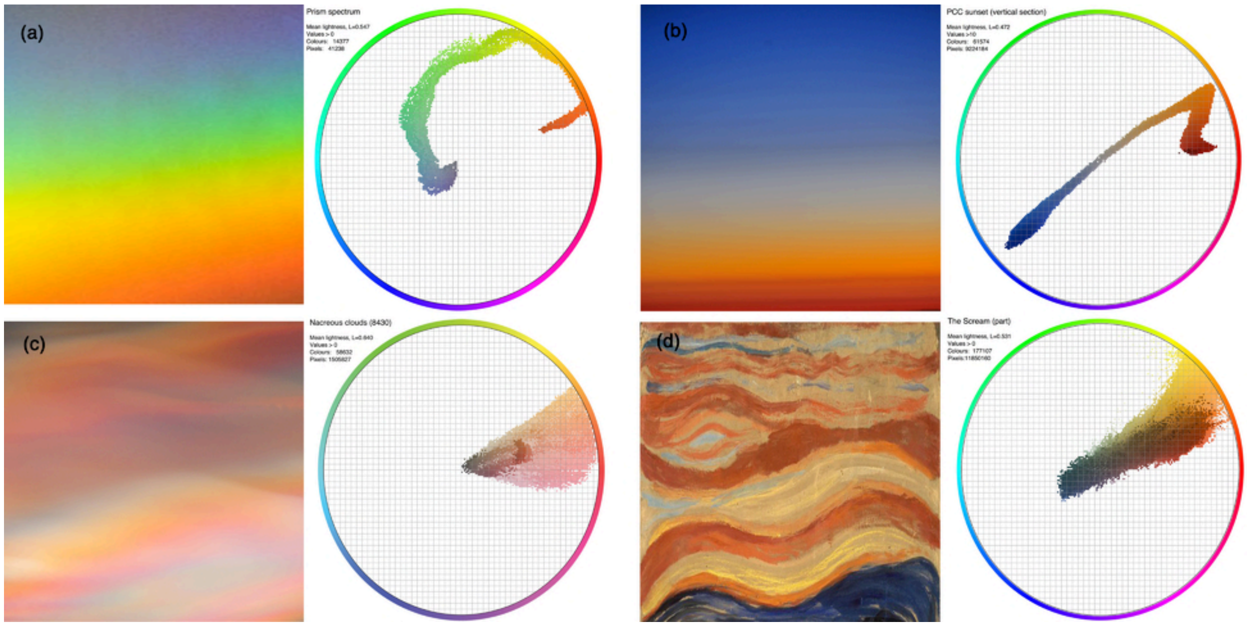

FIG. 5. (a) A rainbow spectrum and the corresponding HSL color wheel. (b) PCC sunset and the corresponding HSL color wheel. (c) Section of a photographo of nacreous clouds and the corresponding HSL color wheel. (d) A section of the "The Scream" and the corresponding HSL color wheel.

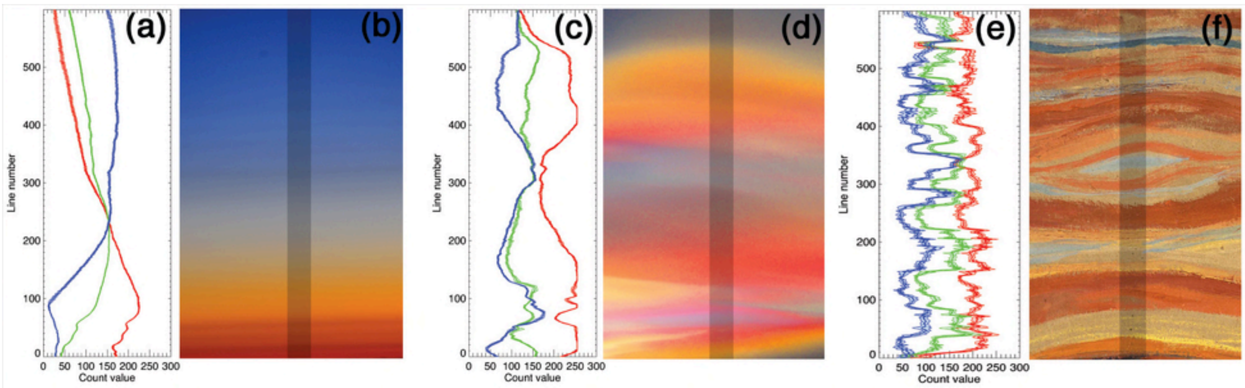

FIG. 6. (a) Mean and standard deviation of a vertical section of the PCC sunset photograph shown in (b)–indicated by semi-transparent rectangle. (c) As for (a) but through a vertical section of the nacreous cloud photograph shown in (d). (e) As for (a) but through a vertical section of "The Scream" pastel painting shown in (f). Each vertical section is 30 pixels wide.

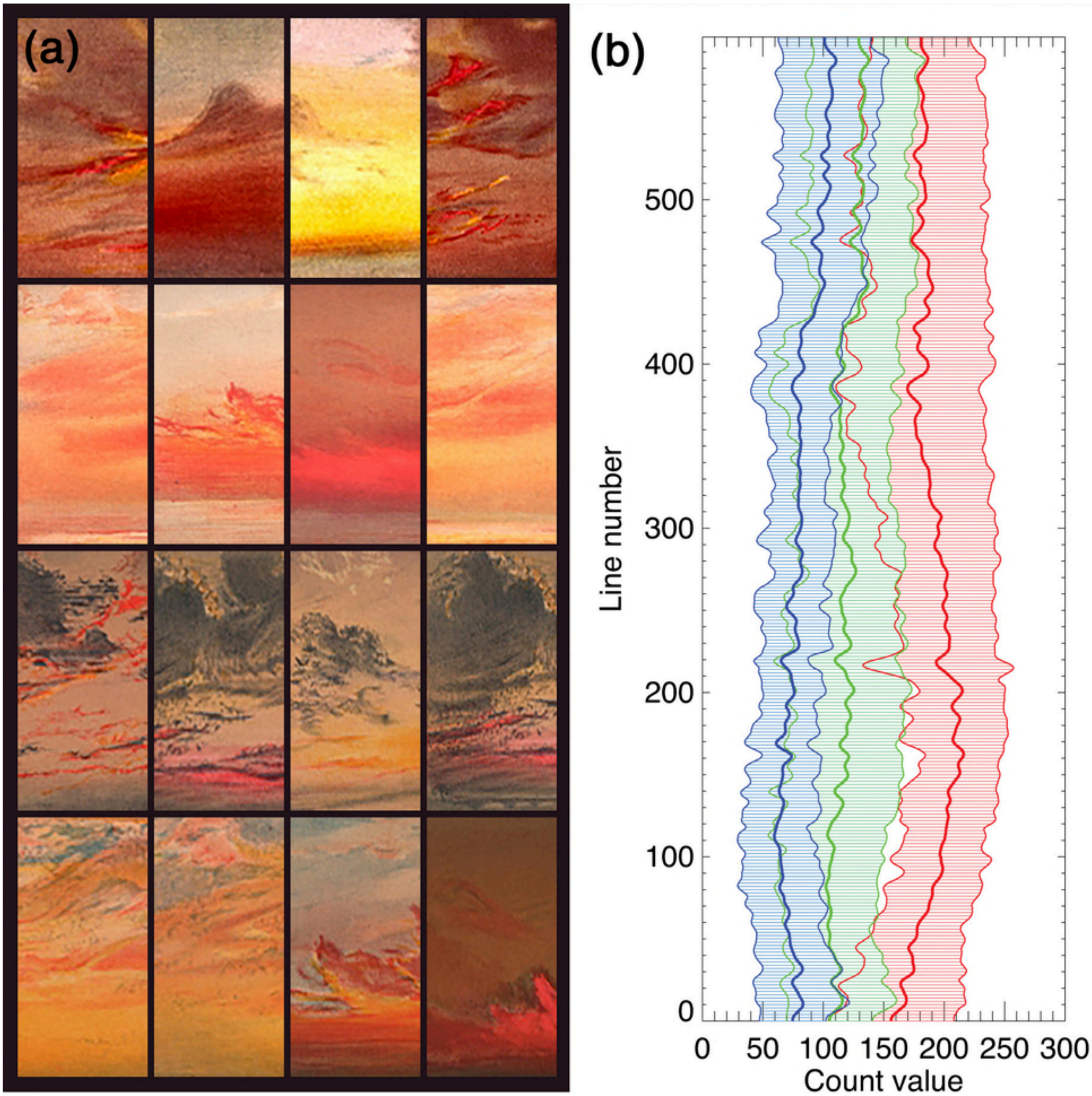

FIG. 7. (a) *Left-hand panels:* Sixteen sections of the sky extracted from photographs of 12 of Ascroft's sketches of sunsets over London. Photographs taken by FP of the original sketches held in the Blythe House archive of the Science Museum, London, UK. (b) *Right-hand side:* Mean and standard deviation of the RGB color components for a 10 pixel-wide vertical transect through the central part of the sections shown in Fig. 7(a). Line number refers to the image line in the vertical direction on each of the sections shown in the left-hand panels. Higher line number corresponds to higher elevation.

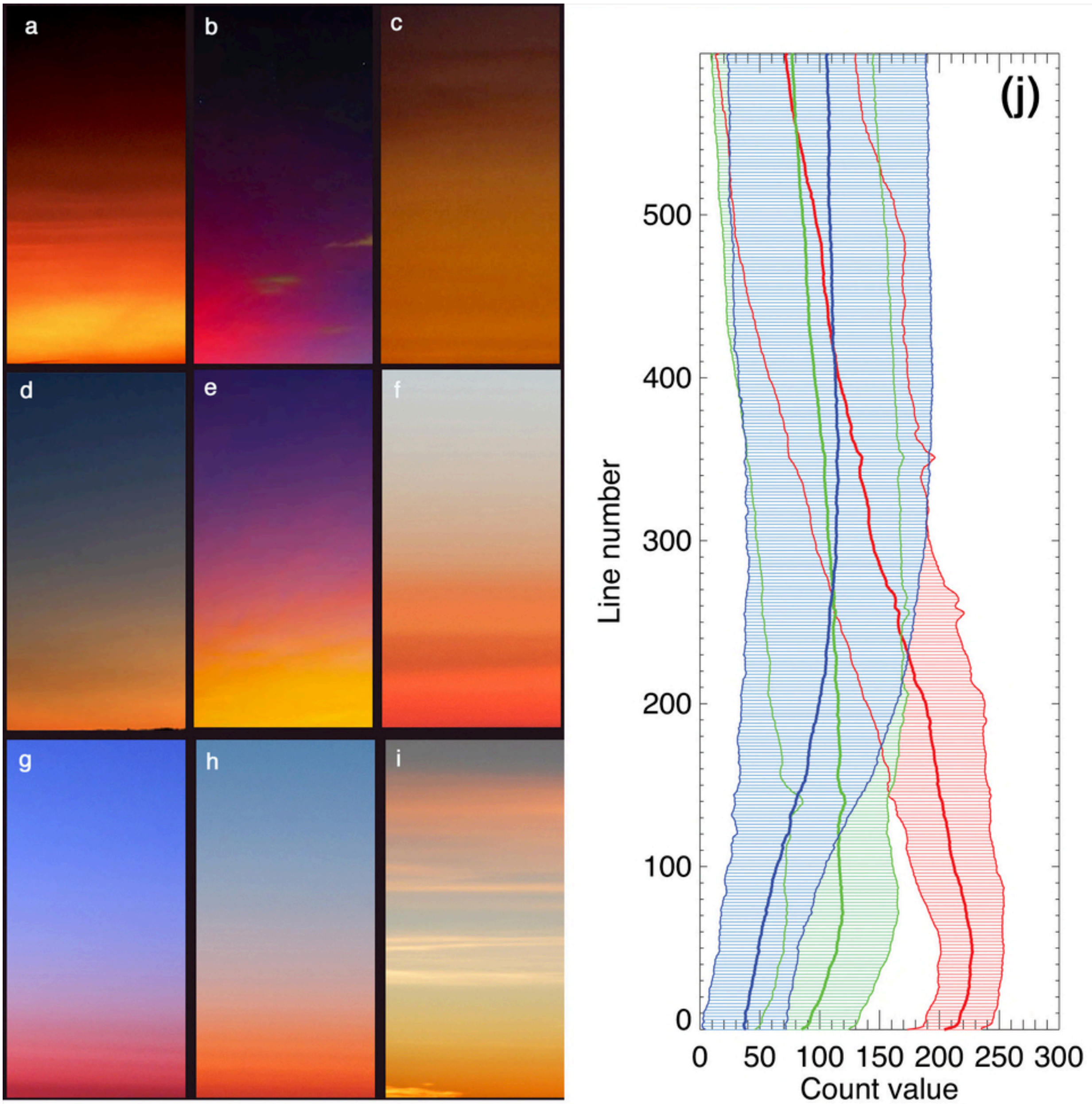

FIG. 8. (a–i)*Left-hand panels:* Sections from the sky regions of nine different photographs of volcanic sunsets. Credits: a. CSIRO, Atmospheric research (Pinatubo, 1991, Melbourne, Australia). b. Helio Vital (Calbuco, 26 May 2014, Santiago, Chile). c. A. Robock (El Chichón, July 1982, Madison, Wisconsin, USA; RGB brightness enhanced by 50% from original photograph). d. Bob King (`https://astrobob.areavoices.com/2008/08/30/volcanic-dust-paints-duluths-sunsets/`) (Kasatochi, August 2008, Duluth, USA). e. Unknown photographer, (Calbuco, May 2014, Chile). f.-i. Captain Klaus Sievers, (various locations and times taken from the cockpit of a commercial jet aircraft). (j) *Right-hand side:* Mean and standard deviation of the RGB color components for a 10 pixel-wide transect through the central part of the sections shown in the left-hand panels.

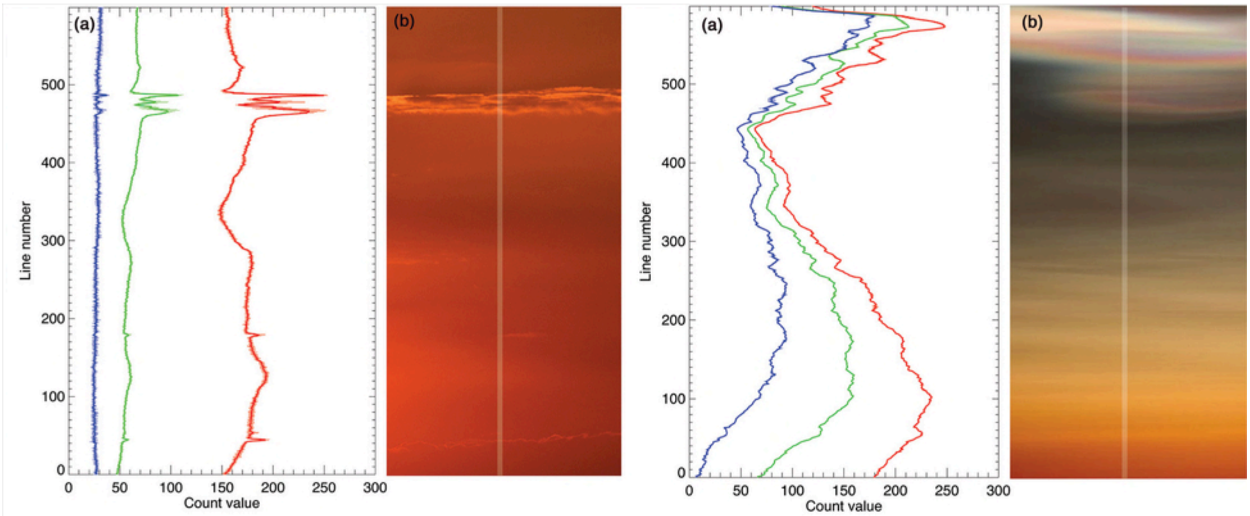

FIG. 9. (a) Variation of the mean and standard deviation of the RGB color components for a 20 pixel-wide vertical transect through the central part of a section of the photograph shown in (b) for a non-volcanic sunset. (c) Variation of the mean and standard deviation of the RGB color components for a 20 pixel-wide vertical transect through the central part of a section of the photograph shown in (d) for a non-volcanic sunset and a nacreous cloud display at higher elevation.